Validation Issues within transmission line modeling in high frequency regions

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VALIDATION ISSUES WITHIN TRANSMISSION LINE MODELING IN HIGH FREQUENCY REGIONS

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Abstract. This paper deals with some possible validation issues that can be met when transmission line theoretical models are compared to integral 3D methods and/or measurements. The main objective of this paper is to show that the choice of the measurement setup is critical as well as the choice of the modeling configuration.

I. INTRODUCTION

Electromagnetic compatibility (EMC) compliance of a vehicle is a mandatory requirement in relation with many specific standards. Due to cost and time-to-market issues, the EMC of a vehicle must be considered in the early stage of a vehicle project development. This can only be done through numerical simulations since even the prototype is not yet available.

In the automotive domain, an important point in the electromagnetic compatibility investigations concerns the electromagnetic field coupling to the wires in the harnesses, since they play an important role in the propagation of induced currents and voltages to the input/output pins of the equipment, which may lead to malfunctions. Alternatively, they may also contribute to unintentional electromagnetic radiations and crosstalk coupling with neighboring wires and equipment.

Ideally, the numerical simulations would be carried out using software tools based on the resolution of Maxwell's equations and without any approximation. Hence, this requires meshing all the conductors in the harness and the entire metallic structure of the vehicle which is totally unrealistic due to the memory requirements and simulation time of such methods.

An alternative solution that is frequently used is the classical transmission line theory (TLT) under its multi-conductor formulation and in which the terminal loads represent the equipment. In this case, the calculation is made in two steps, where two decoupled problems are solved successively. In the first step, only the structure of the vehicle is meshed (in the absence of the harnesses and the equipment) in order to calculate the electromagnetic fields through 3D Maxwell's equations solvers. Then, in the second step, a classical TLT solver is used to calculate the induced currents and voltages on the wires, using the electromagnetic field sources calculated in the first step. If one is interested in the radiated fields from the wire, the two steps are permuted.

However, this theory is limited by its assumptions [1], [2] based mainly on the condition that the distance between the line and its return path should be much smaller than the minimum considered wavelength of the incident electromagnetic field. Moreover, the classical TLT is not valid at resonant frequencies even when the above-mentioned distance condition is satisfied. This statement is partly due to the neglecting of the radiation resistance and to the somewhat undefined boundary conditions at the ends of the wires as discussed in this paper.

Thus, several techniques modifying the telegrapher's equations in order to be valid at frequencies for which the radiation resistance can no longer be neglected have already been developed for several applications [3]–[6]. But these solutions either need entirely new software development or are based on time consuming iterative methods.

The authors have also developed a new transmission line (TL) model accounting for radiation losses. The new model leads to satisfactory results comparable to those obtained with full-wave solvers or measurements, while keeping the simple TLT mathematical structure [7], [8].

More specifically, this paper is dedicated to show some of the validation issues that can be met when trying to compare theoretical approximate models (TLT), to rigorous Maxwell's equations resolution or to measurements. Hence, the next section briefly presents the issues encountered. Section III gives some explanations to the differences between the results given by the different approaches. Section IV deals with a possible validation solution and presents the obtained results. Section V concludes this paper.

II. PROBLEMATIC

II.1. Context

From Maxwell's equations and using the thin wire approximation, it is shown that the field-to-wire coupling (Fig. 1) can be represented by the following equations [7], [8]

$$\frac{dV^s(z)}{dz} + I(z)(j\omega L^{HF} + R^{HF} + R_+) = E_z^e(h,z) \quad (1)$$

$$\frac{dI(z)}{dz} + V^s(z)(j\omega C^{HF} + G^{HF}) = 0 \quad (2)$$

where V^s stands for the voltage related to the scattered electric field, I the current, E_z^e the exciting incident electric field, R^{HF}, L^{HF}, C^{HF} and G^{HF} are respectively the high frequency per-unit-length resistance, inductance, capacitance and conductance, and finally R_+ is an additional resistance proportional to the high frequency characteristic impedance of the line. All these parameters and their signification are given in [7], [8].

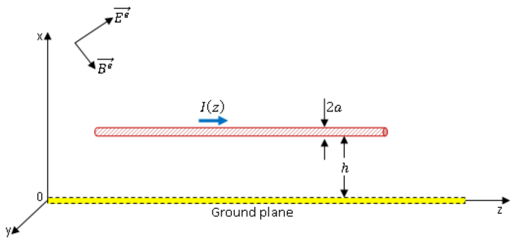


Fig. 1. Original geometry of the TLT derivation

The above new model is called the modified enhanced transmission line theory (METLT). In order to validate the METLT, its results should be compared to those obtained through measurements or a full-wave solver (e.g. a Method of Moments – MoM solver). However, in order to assess the TLT (either the classical or the METLT) results, there is a last limitation to take into account: the line extremities. In fact, the TLT derivation does neither consider the vertical wire terminations nor any other extremity terminations (as shown in Fig. 1). Hence, the coupling between the horizontal wire and the vertical ones is not taken into account since the last ones do not explicitly exist.

Indeed, the derivation of the METLT equations is performed, as in most transmission line models, for a simple non terminated wire above a perfect electric conductor (PEC) ground plane (Fig. 1) applying image theory. Therefore, no connection between the signal conductor and the ground plane is considered.

However, for practical situations as well as for full-wave solvers, the horizontal wire must be connected to the ground plane in some way. Moreover, in reality, the wire is always terminated by electronic or electrical equipment. A piece of equipment may be considered as a black box that contains several electronic components, a metallic structure and an internal ground plane that is connected to the global ground plane through a return wire (Fig. 2).

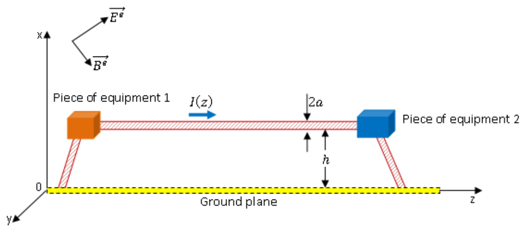


Fig. 2. Possible practical situation

Besides, the path of the wire connecting the internal ground plane to the global ground plane may be vertical or not. Generally, the internal ground plane (inside of a piece of equipment) is connected through a wire to the metallic structure of the piece of equipment that is itself connected to the global plane through another wire.

Furthermore, the piece of equipment may contain resistors, inductors, capacitors, non-conductive substrates and conducting traces.

Thus, to simplify such complicated situations, equipment are considered only from their input impedance interface, and the path of the return current is assumed vertical from the signal wire to the ground plane (Fig. 3).

Generally, to materialize the path of the return current, engineers and researchers proceed in the following way:

- They use vertical wires in the TLT and full-wave solvers to connect the signal conductors to the reference conductor (software limitation)
- They use vertical panels (easier to handle) in experiment setups

However, this may lead to some substantial differences that are due to the way these terminations are considered in each case (TLT, full-wave solver or measurements).

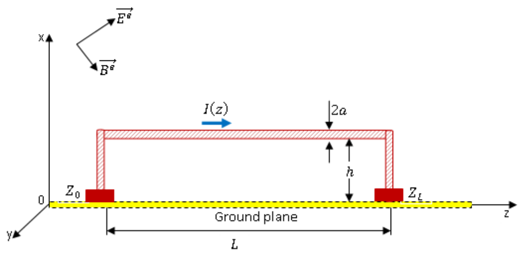


Fig. 3. Actual geometry of the validation

In the TLT, the vertical wires are considered as non-radiating and are always taken into account through lengthening the current path. This is the reason why the horizontal wire is generally lengthened by its height in the classical TLT as well as in the METLT [9], [10].

Nevertheless, in the full-wave solvers, incorporating the vertical wires requires them to be meshed and characterized as radiating antennas as well as the horizontal wire. Thus, the coupling between both horizontal and vertical parts is also taken into account.

In the case of measurements, where vertical panels are generally used instead of vertical wires, the situation may be completely different according to the dimensions of the panels and the frequency at which the study is performed [11]. Moreover, even if it may seem evident, the behavior of vertical wires may be completely different from that of vertical panels.

Since the TLT (classical or modified enhanced) equations are derived in the absence of any kind of terminations, materializing the current return path by vertical wires should not be considered as being without consequences on the physical phenomena occurring at the line extremities (modification of the boundary conditions).

II.2. Effects of the terminations

In the following, we will show the effect, on the final results, of the materialization model of the current return path between the horizontal wire and the reference ground plane.
Thus, the circuit described in Fig. 4 is studied. The circuit is composed of a PEC uncoated wire of length $L=1$ m, radius $a=0.75$ mm at a height $h=10$ cm above a PEC ground plane. The wire is fed by a voltage source $e=0.632$ V and loaded by two impedances $Z0=50$ Ω and $ZL=50$ Ω.

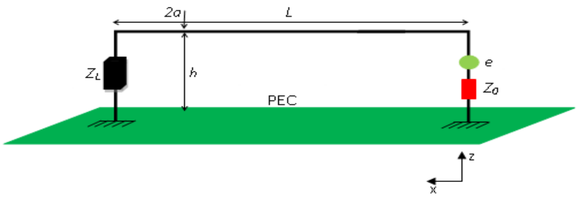
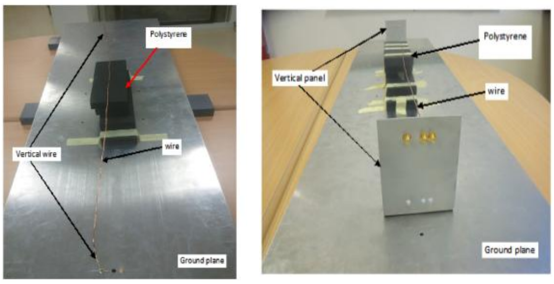


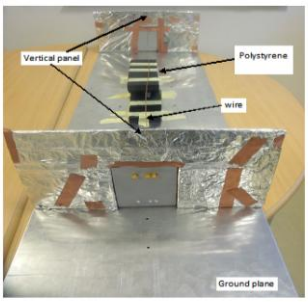
Fig. 4. Validation circuit

The connection between the horizontal wire and ground plane is materialized by vertical wires (a) and vertical panels (b) and (c) of different sizes (Fig. 5). The geometrical dimensions of the vertical panels are:

- Small panels: height=12 cm, width=10 cm
- Large panels: height=20 cm, width=40 cm



a) Vertical wires b) Small panels



c) Large panels

Fig. 5. Measurement setup with different terminal configurations

Both panels have a thickness of 3 mm. In the measurement setup, the ground plane is 40 cm wide, 1.50 m long and 3 mm high. In the MoM, the vertical panels are just PEC rectangles without any thickness and the ground plane is an infinite PEC.
As expected, the terminations of the wire play an important role in the appreciation of the TLT (classical or METLT) results as shown in Fig. 6. Note that, in the case of the vertical wires, the current is observed at the extremity of the vertical wire, whereas in the case of the vertical panels, the current is observed at the end of the horizontal wire only (the current path is not lengthened by the height). This is the reason of the shift of the resonant frequencies between the results with the vertical wires and those with the panels.
In the low frequency region (when the applicability conditions of the classical TLT are verified), materializing the current return path between the horizontal wire and the ground plane by means of vertical wires, small or large vertical panels does not affect the current magnitudes at the end of the wire.
It is probably for this reason that vertical panels are often used in measurement setups while vertical wires are used in simulation (either in a full-wave solver or in TLT).
At higher frequencies, the interpretation of the results is more complicated. Indeed, the current magnitude at the end of the wire varies significantly among the different configurations.
When small panels are used, we notice that the current magnitude at the far end load decreases in the intermediate frequency region (between 400 MHz that corresponds to $h=\lambda/8$ and 600 MHz that corresponds to $h=\lambda/5$) and is lower than the one predicted or measured using either larger vertical panels or vertical wires. This means that, in this range of frequencies, the small panels lead to more important energy losses. The losses are certainly due to the radiation occurring at the extremity of the wire, and to the radiation of vertical panels themselves (edge effects). Nevertheless, beyond 600 MHz the current starts to increase, approaching the magnitude of the current in the case of larger vertical panels.

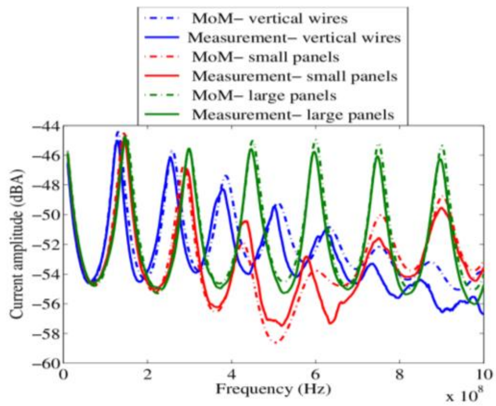


Fig. 6. Current magnitude as a function of the frequency at the end of the transmission line for different terminal configurations

In the case of large panels, whose width is greater than the wire height, the current at the wire extremities nearly conserves its magnitude even at higher orders of resonances. This means that the classical TLT can be used even if it is well known that theoretically, it is no longer applicable considering the case of the only wire with or without vertical wires at the extremities.
Thus, it seems apparently contradictory since, as it is known, beyond the validity limit of the classical TLT, the radiation becomes as important as it leads to the decrease of the current on the wire.

Therefore, as expected, the chosen model of the current return path between the horizontal wire and the ground plane affects the current magnitudes and may lead to misinterpretations of the results. We note that, beyond the validity limits of the classical TLT, the predicted current is significantly affected by the terminal conditions: vertical wire or panels and the shape of the used panels (small or large).

III. INTERPRETATIONS

As mentioned previously, the transmission line theory is basically defined for a horizontal wire above an infinite PEC ground plane. Thus, the principle of the TLT imposes that the horizontal wire is not terminated by any configuration connecting it to the ground plane. Besides, the current in the ground plane has the same magnitude as on the wire but flows in the opposite direction (as predicted by image theory).

Therefore, the current path between the ends of the horizontal wire and the ground plane has always been considered as "fictitious".

However, in practical situations, this is not possible. The horizontal wire must be linked to the ground plane by any "real" connection. This is unavoidable in measurements and most simulation configurations.

It was shown in section II that, according to the chosen connection model, the current in the termination loads may be different. Thus, comparing the results predicted by the transmission line approach (classical or modified enhanced) with those of the MoM or measurements may not be possible or even might lead to misinterpretations.

However, for analysis in low frequencies, far from resonant frequencies, all models (vertical wires, different geometrical dimensions of the vertical panels) lead to almost the same results on the radiated electric field magnitude. Hence, this leads to current magnitudes that are comparable using any model and means for which the radiation may be neglected.

Figure 7 shows the effect of the chosen connecting model on the longitudinal near electric field level at 500 MHz and the geometrical dimensions in the case of the vertical panels.

It is interesting to notice that the small panels behave almost as the vertical wires i.e. the radiated energy is not confined between the two panels but is radiated outside. Hence, in this case, part of the electric energy is converted into radiated energy.

It is to be noted that generally, the vertical wires are taken into account by lengthening the horizontal wire by their height. Therefore, this solution leads to represent the vertical wires by the same characteristic impedance as the horizontal one. This is equivalent to consider that both parts are behaving in the same way. However, this can only be considered as a good approximation in low frequency regions and far from resonances. Hence, considering the vertical wires through merely lengthening the horizontal one is just a rough approximation especially at resonances. Moreover, at resonant frequencies, the radiated electric field magnitude from the vertical wires is more important than when vertical panels are used. This is the reason of the observed differences in the current magnitudes between the vertical wires and the vertical panel configurations.

In the case of small panels, we highlighted in Fig. 6 that in the intermediate frequency region (between $h = \lambda/8$ and $h = \lambda/5$), the current magnitude starts to decrease and has magnitudes that are smaller than predicted in the case of the vertical wires Thus, this means that there is more energy losses. This can be explained by the edge effects and the behavior of the vertical panels at their resonant frequencies (as shown in Fig. 7 at 500 MHz). This is confirmed by the fact that, in the case of the large panels, the phenomenon of current decrease is not observed, and the corresponding near electric field mapping shows that there is no radiated energy beyond the panels (x direction).

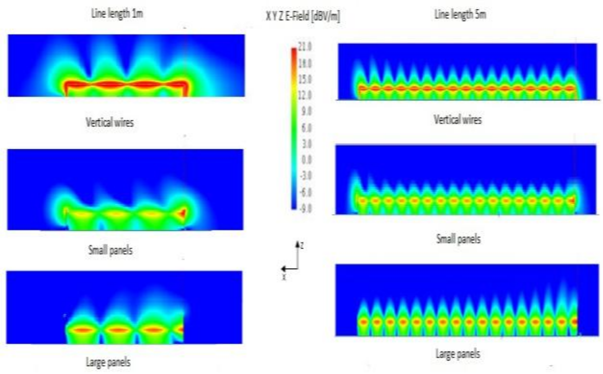


Fig. 7. Near electric field mapping in the x-z plane, for two different lengths of horizontal wire and for several types of wire extremities, at a frequency f=500 MHz (intermediate frequency where the current magnitude decreases when small panels are used)

In general, the use of the vertical panels leads to higher current magnitudes in high frequency regions as shown in the previous section. Thus, the bigger the panels are, the higher is the current magnitude.

We have even seen that when large vertical panels are used, the current magnitude at the load is predictable with classical TLT (there is almost no decrease in current magnitude).

Indeed, when the vertical panels have dimensions that are sufficiently larger compared to the height of the wire (the large panels in our study), the geometry they form can be considered as a 1D cavity that resembles somehow a Fabry-Perot cavity (Fig. 7). Indeed, even if the line is lengthened, the electromagnetic field (Fig. 7) and the current (Fig. 8) behave in the same manner as in the case of the shorter line.

Thus, the electromagnetic waves in this cavity can be considered as a standing wave up to a certain threshold frequency. This is the reason why, when the panels are large, the MoM predicts results that are comparable to those calculated by the classical TLT.

From a mathematical and physical point of view, this can be explained as follows: since the TLT (classical or modified enhanced) equations are derived in the absence of any kind of terminations, materializing the current return path by vertical wires should not be considered as being without consequences on the physical phenomena occurring at the line extremities (modification of the boundary conditions).

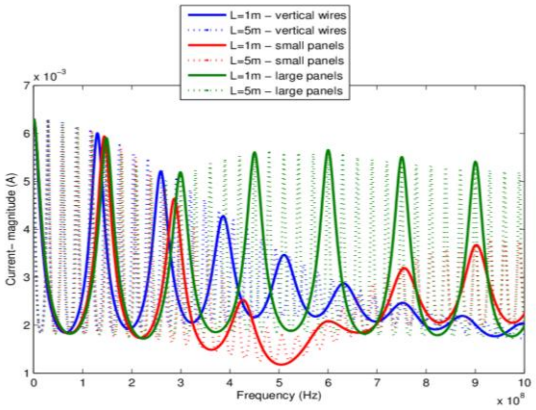


Fig. 8. Current magnitude as a function of the frequency at the end of the transmission line for two different lengths of horizontal wire and for several types of wire extremities

Hence, this can be introduced theoretically by the fact that the Green's function is now only valid for a reduced geometrical domain, shorter than it was when the wire is considered as non-terminated.

Generally, and for reasonable frequencies ($kh <\cong 1$), the validity domain of the Green's function is reduced by the double of the wire height at both sides [1].

Indeed, in all this study (both in the classical and modified enhanced TLT), the Green's function contains only two terms: the first is related to the contributions of the actual conductor and the second to those of its image.

Thus, this representation is only valid when the contributions due to other components (like the vertical wires or nearby metallic structures) are negligible. Therefore, any presence of vertical wires (or metallic structures) at the wire extremities will affect the electromagnetic field at their vicinities (Fig. 9). This leads to an incomplete Green's function near these regions, since the considered Green's function does not take into account the contributions of the wire extremities.

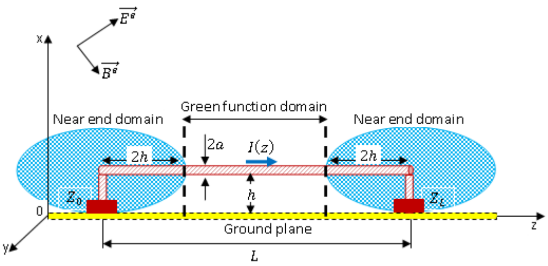


Fig. 9. Actual domain of validity of the Green's function

IV. VALIDATION

As stated in the previous section and in order to show the expected limitation of the classical TLT, the vertical wires are more suited to represent the connection between the horizontal wire and the reference ground plane. Hence, only vertical wires are considered in the following to validate the METLT model.

The same configuration described in Fig. 4 is studied using the METLT p.u.l. parameters, the classical ones and the results are compared to MoM ones. However, hereafter, the wire is fed by a voltage source $e=1$ V and loaded by two impedances $Z0=0\ \Omega$ and $ZL=1\ \Omega$.

Fig. 10 shows that the classical p.u.l. parameters lead to currents of constant magnitudes at resonant frequencies, the METLT parameters lead to maximum magnitudes that follow the pattern of those obtained with the MoM.

Indeed, in this case, the radiation resistance is greater than the load resistances, which makes this configuration critical. Therefore, using the classical TLT, even when its applicability conditions are fulfilled, leads to unrealistic magnitudes of resonances. However, the use of the METLT leads to results comparable to those obtained by the MoM. Thus, when the classical TLT leads to 0 dB (which means that there is no losses) at resonances, the modified enhanced one predicts -13 dB like the MoM does at the first resonance frequency of 130 MHz.

In the higher frequency range, when the classical parameters lead to a current magnitude of 0 dB at 750 MHz, the modified enhanced ones predict -40 dB whereas the full-wave solver leads to -43 dB. This means that the modified enhanced TLT is still more accurate than the classical one but its results start to diverge from the MoM results at this frequency (Fig. 10).

This can be explained by the effect of the vertical wires that are more accurately modeled in the full-wave solver where they are meshed and considered as radiating antennas, whereas they are considered in the TL approach as only an extension to the horizontal wire. Hence, this shows that, the vertical wires should also be modeled more accurately to reach results that are similar to those of the MoM.

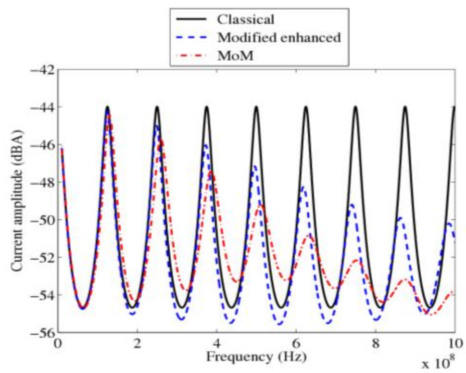


Fig. 10. Current magnitudes as a function of the frequency at the end of the TL, using the modified enhanced p.u.l. parameters

V. CONCLUSIONS

In this paper, it is shown that comparing measurement or full-wave results with TLT (classical or modified enhanced) results may be a hard task. This is true especially for the METLT since it is intended to be valid in high frequency regions (beyond the limits of the classical TLT).

Indeed, it is recalled that the TLT in its general form (classical or modified enhanced) is always made for the case of a horizontal infinite (non-terminated) wire above an infinite PEC ground plane. Therefore, no connections between the horizontal wire and the ground plane are considered.

However, in practical situations, the connection between the wire and the ground plane is physically present. In order to close the current path, one adds vertical panels in their measurement setup and vertical wires in full-wave solvers or TLT models. Hence, the current flow between the horizontal wire and the ground plane is materialized by two different means: a vertical wire and a vertical panel.

These two solutions are both acceptable only in low frequency regions (when the classical TLT assumptions are fulfilled) where the model used (with vertical wires or panels) does not have a significant impact on the final results (except at resonant frequencies).

Thus, in high frequency regions (when the height of the wire is no longer sufficiently smaller compared to the minimum significant wavelength of the current), using vertical wires or panels lead to large differences in the results. This is shown to be related to the actual nature of the connection and its dimensions (in the case of the vertical panels).

Indeed, in TLT the connection is generally materialized by a non-radiating vertical wire. Nevertheless, when the same circuit is simulated in a full-wave solver, all its parts are meshed and considered as being antennas elements. Then, the vertical wires radiate and interact with the horizontal wire.

Moreover, when vertical panels are used in measurements or full-wave solvers, they are still modeled through vertical wires in the TLT. However, this is shown to be inaccurate since all the physical properties of the circuit are modified and energy may even be confined between the panels, according to their geometrical dimensions.

Thus, modeling the connection between the horizontal wire and the return conductor by vertical wires may be the most accurate way to validate "an all-wire" classical or modified-enhanced TLT model. However, the same configuration with vertical wires must be modeled in a full-wave solver or measured in an experimental setup.

The results obtained by the new model are comparable to those obtained with a full-wave software even at resonant frequencies.

However, in high frequency regions, some apparent differences with the full-wave formalism start to rise which is shown to be the consequence of the vertical wires. Indeed, in the full-wave solver they are meshed and coupled with the horizontal wire, whereas in the METLT, they are just taken into account by lengthening the horizontal wire.

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